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REPLICATION AND EXTENSION OF HUMAN SENSORY CAPABILITIES IN HEAR--ETC(U)

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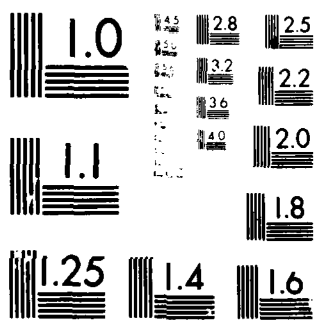

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REPLICATION AND EXTENSION OF HUMAN SENSORY CAPABILITIES IN HEARING

DW Martin

April 1980

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The research reported here was conducted for the Advanced Teleoperator Technology Project, a NAVMAT exploratory development program.

Part of this program's initial effort is directed toward transmitting high quality sensory information to an operator from a potentially hazardous remote location. This paper concerns the investigation of one sensory channel – the auditory system.

Research and preparation for this paper was conducted by the author as part of the New Professional Program at the Naval Ocean Systems Center, Hawaii Laboratory. The author gratefully acknowledges the assistance of David Smith and Frank Armogida, principal investigators of the Advanced Teleoperator Technology Program. The suggestions and technical criticisms of Robert Gales, Code 5121 and Whitlow Au, Code 512 are also appreciated.

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The human auditory system is investigated to determine the parameters necessary to design a remote auditory system. Special attention is given to the development of human localization and unaided echolocation skills. Monaural and binaural localization are examined, as well as dummy head design, and design considerations for an underwater auditory system. Finally, active sonar systems are discussed in terms of their applicability to human sensory capabilities in hearing.

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INTRODUCTION

The following is a description of the desired capabilities of a system which, when placed in a distant and potentially hostile environment, would provide a human operator with an accurate representation of the sound field in that environment. Optimally, this system would provide the human with auditory sensory inputs equivalent to those which he would actually experience in the foreign environment. In addition, it would provide extensions of human sensory capability including the following: transmission and display of ultrasonic and infrasonic information, an active sonar system which would utilize and extend present human echolocation capabilities, and the ability to hear and accurately localize sounds in underwater environments.

A great deal of research has been done in attempts to reproduce human hearing and localization abilities with a mechanical system. These investigations have been carried out primarily by two groups: members of the recording industry who are interested in providing listeners with spatial displays of music, and designers of hearing aids who are interested in development of dummy heads for testing and evaluation. Monaural hearing and localization has been demonstrated with artificial pinnae (Batteau, 1967; Shaw, 1979), and binaural localization has been accomplished through the use of dummy heads (Burkhard and Sachs, 1975; Kuhn, 1979A, 1979B). The designers of dummy heads have sought to replicate binaural intensity differences resulting from head baffle and shadow effects, and binaural phase differences resulting from path length differences between the ears.

Several attempts have been made to replicate binaural hearing by replacing the head and pinna structures with models of various shapes and materials (Wonsdronk, 1959; Wiener, 1947A, 1947B). The performance of such models is necessarily suboptimal, and they have met with varying degrees of success, depending on their applications. Variation of some head and pinna parameters produces only second-order effects on localization, whereas variation in others produces more marked effects. Certainly, the more closely a model resembles the human head and ears, the more realistic will be the operator's perception of the sound field. However, many parameters need not be duplicated in order to provide accurate and unambiguous sound localization, given that time is available for training the operator with the suboptimal system, and he is able to learn new localization cues. That is, he must be able to learn that sounds which he perceives at a given angle may actually be shifted by some constant amount.

Many investigators have also examined signal design and array design characteristics for active sonars. Most of this work has simply involved target detection, but investigations into target identification and localization have been undertaken in the interest of developing a sonar mobility aid for the blind. Considerable recent work has demonstrated the object discrimination ability of divers using portable underwater sonar systems.

The several sections of this document describe parameters of a system to transfer auditory sensory data to an operator, and the effects which might be expected if these parameters are varied. First is a description of monaural hearing and localization and related design

of an artificial pinna. Next is a presentation of information about binaural localization cues and a discussion of their relative saliency as a function of various dummy head parameters. This is followed by a brief discussion of the design of a system for passive hearing and localization under water. The final two sections discuss implementation of active sonar for echolocation. Vast differences exist in echo discrimination capabilities in air and water, due to impedance mismatching between the target and the medium. Thus, the first implementation section presents information on what is achievable in terms of obstacle detection and discrimination by ear without the aid of extra equipment. This form of sonar is quite limited, although with practice most people can at least avoid obstacles. The second implementation section discusses various aspects of signal design for active sonar. The type of signal and beam pattern which is most desirable depends on the types of discriminations being attempted.

MONAURAL LOCALIZATION

Monaural localization is accomplished primarily by the pinna, and to some extent by reflections from the torso (Butler, 1969; Kuhn, 1979B; Batteau, 1962, 1967). Localization in the vertical plane is almost exclusively monaural (Butler, 1969), and monaural cues contribute to localization in the azimuthal plane, although accurate localization in azimuth requires a combination of monaural and binaural cues. Localization of sound in the azimuthal plane is possible monaurally, but performance is severely degraded from that possible with two ears (Butler, 1969).

Essentially, the pinna acts as an antenna whose directivity pattern is extremely frequency-dependent. Localization is accomplished via time delays between direct and pinna-reflected sound (Wright, Hebrank, and Wilson, 1974), with the delays being a function both of frequency and the relative orientation of observer and sound source. The pinna is a very poor sound collector at low frequencies (Shaw, 1979), and above 5 kHz, localization is largely the result of high-order transverse modes within the pinna (Kuhn, 1979A, 1979B). The shape of the pinna is ideally suited for localizing broadband signals. Components of a complex sound arriving at different parts of the pinna take paths of different lengths by being multiply reflected to reach the canal entrance (Konishi, 1976). Batteau (1967) has described localization as resulting from differences in sound arrival times at the eardrum. He has shown that a unique set of arrival times is possible for each set of spatial coordinates. Since the sound pressure transformation from the ear canal entrance to the eardrum is independent of the sound direction (Wiener and Ross, 1946; Shaw and Teranishi, 1968), the arrival time differences must result from multiple reflections by the complex pinna surfaces. Therefore, in designing an *artificial pinna*, it is essential that the pinna contours and size be very accurate.

Monaural localization can be simulated quite effectively by mounting a small microphone at the canal entrance of an artificial pinna and presenting the signals to an operator wearing headphones. As mentioned earlier, the directivity pattern of the pinna, and consequently its size and shape, are extremely critical for accurate localization. In the design of an artificial auditory system, it would be desirable to allow for interchangeable pinnae (Burkhard and Sachs, 1975). Given such a system, a model could be made of each operator's pinna so as to minimize the number of new localization cues he must learn. Sizes and shapes of pinnae differ greatly among individuals (Burkhard and Sachs, 1975), and obviously, each person has learned to localize sounds through his own ears. If the system were designed with a standard "average" pinna, it is probable that unambiguous localization would still be possible. It seems plausible that operators could learn the localization cues associated with a new pinna, but the evidence concerning this point is inconclusive. In one study summarized by Trahiotis and Robinson (1979), subjects were presented with binaural recordings made via miniature microphones mounted in the ears of other subjects. One observer who performed poorly on a localization task using his own pinna, did quite well using recordings from the pinna of another subject. Other subjects were also unable to localize with the stimuli recorded in the pinna of the first observer. This suggests two major results. First, the pinnae of some people are poorly suited to localization, and secondly, it is possible for an observer to learn new localization cues associated with a different pinna.

Since multiple reflections in the pinna are so critical to localization, it seems that far too little attention has been given in the literature to the choice of materials for constructing artificial pinnae. Most investigators have used either rubber or plastic (Burkhard and Sachs, 1975; Shaw, 1968; Batteau, 1963). The effect which another, possibly more reflective, material would have on pinna directivity is not known to this author.

In order to replicate human hearing, the microphone mounted in the pinna should optimally have a frequency response from 20 Hz to 20 kHz, and a dynamic range from 0-130 dB re 20 μPa. Of course, reduction of the frequency response to a narrower band, or its extension to ultrasonic and infrasonic regions with appropriate methods of display, may be desirable, depending on the sounds which must be received. For example, if the system's only purpose were to transmit speech signals, a frequency response from 300 Hz to 5 kHz, slightly exceeding that in most telephones, would probably be sufficient. The microphone should be no larger than one half inch in diameter, and because of its small size and location within the highly directional pinna, the microphone directivity pattern is not critical (Lybarger and Barron, 1965).

As mentioned earlier, the best reproduction of the sound field would be achieved with the microphone mounted at the entrance to the ear canal of the artificial head, and with the operator wearing headphones. The transfer function of the ear canal is effectively independent of orientation with respect to the sound source (Wiener and Ross, 1946; Shaw and Teranishi, 1968). However, the transfer function is extremely frequency dependent, tending to amplify frequencies in the 1-5 kHz range. The most accurate reproduction will be obtained if the operator's own canal performs this frequency-dependent amplification, i.e., it would be undesirable to duplicate canal resonances by mounting the microphone at the drum location.

The headphones worn by the operator should reproduce the sound field at the same relative location where it was picked up, i.e., at the canal entrance. Damaske (1971) has attempted to reproduce via loudspeakers the sounds picked up by a dummy head. Accurate localization is not achieved in these circumstances because the sound which is initially received within the ear is reproduced into the entire room. The desired modes are not excited, nor will the directivity pattern at the ear be accurate since it will be modified by the acoustics of the listening room, by the beam pattern of the loudspeakers, and by the distance and orientation of the loudspeakers with respect to the ears.

BINAURAL LOCALIZATION AND DUMMY HEAD DESIGN

Determination of the direction of a sound source is greatly enhanced by the use of binaural cues in conjunction with the monaural cues discussed in the previous section. Vertical localization, which uses mainly monaural cues, is much less accurate than is localization in azimuth which employs both monaural and binaural cues. The advantages gained by two ears separated by an obstacle, the head, are most apparent when discriminating between closely spaced sources which are narrowband and of high frequency (Butler, 1969).

It is well known that people can localize broadband sources more easily than narrowband sources (Konishi, 1976). Altes (1978) has shown on theoretical grounds that accurate, unambiguous localization can be accomplished in both azimuth and elevation using only two ears, given the following conditions:

1. The pinna has a sufficiently directional beam pattern.
2. The two ears are acoustically isolated from one another.
3. The width of the signal's autocorrelation function is narrower than the interpinna spacing, i.e., the signal is sufficiently broadband.

Isolation and interpinna spacing are a function of the composition and size of the head. When designing a dummy head, these parameters are often altered from those of a real human head. The effects of such alterations on localization will be discussed later in this section.

Localization at low frequencies is primarily the result of time or phase differences at the two ears. Unless a sound source is located in the median plane of the head, the path lengths to the ears will be different. While it is generally true that the auditory system is insensitive to absolute phase, e.g., identification of a tone as either a sine or cosine wave with no reference for comparison, it is quite sensitive to temporal shifts in the phase of complex stimuli or to phase differences in dichotic stimuli. In such cases, ample reference information is available.

The difference in path lengths between a sound source and each of the two ears is a function of the orientation of the observer and sound source and of the distance between the ears, approximately 19 cm for the average human (Konishi, 1976). Interaural phase differences are valid localization cues only at low frequencies. If the half wavelength of a sound is shorter than the distance between the ears a binaural phase difference of more than 180 degrees results and it is impossible to tell which ear is in the leading phase (Konishi, 1976). For an interpinna distance of 19 cm, the upper frequency limit for binaural phase comparison in air is approximately 900 Hz. Kuhn (1977) has measured 1400-1500 Hz as the frequency above which subjects switch from interaural time difference to interaural intensity difference as a localization cue. Interaural phase difference can be transferred into interaural time difference since the difference in path lengths between the two ears is given by D sin (theta), and the interaural time difference is (D/c)sin (theta), where D is the distance between the ears, theta is the azimuthal angle of the sound source with respect to the median plane, and c is the speed of sound in air.

At high frequencies, localization is governed by differences in intensity at the two ears. If the wavelength of sound is comparable to or smaller than the head diameter, the head acts as a baffle. The intensity at the ear nearest the sound source is increased relative to the free field intensity. Likewise, the shadow effect of the head decreases the intensity at the other ear. Mills (1958) has measured the threshold for interaural intensity differences under optimum conditions to be as small as 0.5 dB. Head diffraction effects can be as large as ±14 dB (Olson and Carhart, 1975; Shaw, 1974).

Many investigators have measured the obstacle effect of the head either to determine optimum microphone placement for hearing aids or to create binaural effects in sound recording. The most obvious conclusion of these studies is that binaural intensity differences caused by head baffle and shadow effects increase as a function of frequency. Localization is therefore more accurate at high frequencies.

The obstacle effect of the head is a function of the head size and shape and the impedances of the materials of which the head is composed. The extent to which these parameters are critical in the design of a dummy head depends greatly on the purpose for which it will be used. Kuhn (1972A), for example, has found that the head's obstacle effect can be closely approximated by a rigid sphere with the same cross section as that of the head. Olson and Carhart (1975) found that head baffle effects were somewhat greater in front than in back, whereas shadow effects were greater in back. This would, of course, not be true for a sphere. Wiener (1947A, 1947B) points out similarities between the diffraction patterns around the head and those around spheres and cylinders. Wonsdronk (1959), on the other hand, found very poor agreement between diffraction patterns around the head as compared with other shapes. Wonsdronk also obtained poor results when measuring diffraction patterns around a plaster cast of a human head. He attributed this poor agreement to differences in surface impedance between the real and artificial heads, an idea which has not been supported by more recent evidence (Burkhard and Sachs, 1975; Kuhn, 1979A). Burkhard and Sachs attribute the failure of Wonsdronk's plaster model to the fact that it was mounted on a highly absorbent medium to serve as a torso. They point out that the human torso is highly reflective, concluding that the plaster head would have given more accurate diffraction patterns were it mounted on a reflective object. The effect of torso reflections on localization will be discussed later in this section.

The following paragraphs discuss the design of a binaural localization system and the predicted effects of changing various parameters from those of a human head. If the purpose of a binaural localization system is to transmit the sound field to an operator without modification, i.e., to create the exact acoustic impression of being present in the foreign environment, it would be necessary to completely replicate the human head, pinnae and torso in all respects. However, many head parameters are not critical acoustically, and the effect of changing these may not even be noticeable. Furthermore, while changes in other design parameters will produce noticeable effects, many deoptimizations will still allow unambiguous localization, given that the operator can learn new localization cues.

The parameters listed below are believed to be most critical in the design of a binaural localization system.

1. Pinna shape and size. As mentioned previously, it may be desirable to design a head with interchangeable pinnae, such that each operator could use the system with models of his own pinnae. The effect of the pinna as an obstacle for creating shadow effects is insignificant in the frequency range of interest (Temby, 1965).

2. Spacing between pinnae – head size.

3. The presence of an obstacle between the ears to create diffraction patterns. The shape of the obstacle will be discussed in a later paragraph.

4. Some degree of acoustic isolation between the pinnae. The impedance mismatch between the obstacle and the air will probably provide sufficient acoustic isolation. This may not be true for underwater localization, where the impedances of the medium and the head are much more closely matched.

5. The presence of a reflecting surface to simulate a torso below the dummy head. Torso reflections are particularly critical to elevation localization (Kuhn, 1979b). Specific effects of torso parameters have been investigated by Burkhard and Sachs (1975), and by Kuhn (1977, 1979A, 1979B). However, for accurate elevation localization, possibly with new cues, it is probably only necessary that a reflecting surface of some arbitrary shape be present below the head.

The parameters listed below are least critical to dummy head design, i.e., they produce only second or higher order effects in diffraction patterns below 10 kHz:

1. Contents of the head cavity.

2. Skin or surface impedance of the head (Burkhard and Sachs, 1975; Kuhn, 1979A).

3. Hair or hair style (Wonsdronk, 1959).

4. Facial features or other geometric fine structure (Kuhn, 1979A). Similar to the pinnae, the facial features are too small when compared to wavelengths of sound to cause much variation in head diffraction.

5. Material of which the head is made (Kuhn, 1979A). As long as the head surface is acoustically reflective, it will serve as a baffle in air. Its impedance reflective, it will serve as baffle in air. Its impedance differs sufficiently from air that the surface may be regarded as having infinite acoustic impedance. This would not be true in water, however, since the acoustic impedance of water is greater than that of air by a factor of 3000 (Kinsler and Frey, 1962). Most hearing under water is accomplished via bone conduction (Hollien, 1973), with

very poor localization, and the material of which an artificial head is composed becomes more critical. Thus, a material which is more acoustically opaque than that of the human head must be used.

As mentioned earlier, intensity differences at the two ears require the presence of an obstacle to produce baffle and shadow effects. An obstacle of virtually any shape will produce such intensity differences (Wiener, 1947A, 1947B; Wonsdronk, 1959). Since the auditory system is sensitive to interaural intensity differences as small as 0.5 dB (Mills, 1958), it seems that the choice of obstacle shapes would not be critical to high frequency localization. However, changes in head shape will affect the azimuthal dependence of interaural intensity differences. When the head is replaced with a rigid sphere, large interaural intensity differences exist when the sound source is located to either side of the head (Kuhn, 1979A). However, with a sphere or any obstacle which has symmetry between the front and back halves, front-back localization errors will occur for sound sources located in the median plane (Canby, 1977). Discriminations between front and back are ambiguous in such cases because the sound field will be identical whether the sound source is in front or in back of the head. This is not true for a real head, where differences in baffle and shadow effects have been noted between front and back (Temby, 1965; Olson and Carhart, 1975).

In the opinion of this writer, an artificial head made from an obstacle of virtually any shape should allow unambiguous localization, provided it is large enough to act as a baffle in the desired frequency range. Certainly, new localization cues would have to be learned if, for example, an artificial head were cylindrical (Wiener, 1947B). However, such a shape would produce azimuth-dependent interaural intensity differences, thus allowing unambiguous localization. Again, front-back ambiguities will result if the front and back halves of the obstacle are symmetrical, so it seems reasonable to avoid this situation in the choice of obstacle shapes.

When subjects wearing headphones are presented with sounds picked up via a dummy head, the effect is initially that of lateralization rather than localization. That is, when subjects are presented with dichotic stimuli through headphones, the sound images are perceived as originating somewhere in the head. However, when asked to point in the direction of the sound source in space, Molino (1974) has shown that subjects can accurately localize the source in the azimuthal plane.

DESIGN CONSIDERATIONS FOR AN UNDERWATER AUDITORY SYSTEM

If a dummy head system were designed to provide monaural and binaural localization capabilities under water, it would, of necessity, be much different from that discussed earlier. The differences between hearing under water and that in air are governed by two primary factors. First, the speed of sound in water, and therefore the wavelength at any given frequency, is increased by a factor of five. Additionally, the acoustic impedance of water is greater than that of air by a factor of 3000 (Kinsler and Frey, 1962). These differences result in a number of disadvantages for underwater localization as follows:

1. The low frequency range over which the pinna is a poor sound collector (Shaw, 1979) is increased by a factor of five. In fact, the pinna contributes very little to underwater localization (Hollien and Feinstein, 1975).

2. Interaural time differences resulting from differences in path lengths to the two ears are reduced by a factor of five.

3. The ratio of interpinna spacing to wavelength is decreased by the same factor.

4. The head is small compared to a wavelength at much higher frequencies in water. Therefore, interaural intensity differences at any frequency, caused by the head's baffle and shadow effects, are greatly reduced.

5. Human underwater hearing is accomplished primarily via bone conduction (Hollien, 1973; Hollien and Feinstein, 1975). The impedance of the head is much more closely matched to water than to air; thus, the head does not simply act as a reflector (Hollien and Feinstein, 1975).

6. As a result of bone conduction, the degree of acoustic isolation between the ears is greatly reduced.

All of the factors which contribute to sound localization in air are degraded in water. These considerations lead to the initial impression that underwater localization by a submerged human head is impossible, a view which was commonly held for many years. However, several studies have shown that sound localization is possible under water, although it is considerably less accurate than in air (Feinstein, 1966, 1973; Hollien, 1973). Subjects are quite accurate at left-right discriminations, and they can identify the quadrant in which a sound source is located, but discrimination between closely spaced sources is poor. Feinstein (1966) showed that divers could accurately make left-right discriminations when sources were only fifteen degrees off the midline. Hollien (1973) found that low frequency and/or broadband stimuli were localized most accurately under water.

While the magnitudes of localization cues are much greater in air than in water, it has been postulated that localization is possible with cues of much smaller magnitude (Feinstein, 1973; Hollien, 1973). Thus, arrival time differences at the ears may still be sufficient to allow crude localization under water. Additionally, Hollien postulates that localization based on

intensity differences may be possible in bone-conduction hearing due to the angular dependence of the head's sensitivity to skull-conducted sound. However, a greater degree of isolation between the ears would be required to make maximal use of this cue. Norman et al. (1971) report that the localization ability of some fish is enhanced by the fact that their hearing mechanisms are acoustically isolated via cartilage. Such isolation is found in the hearing mechanisms of cetacea, which exhibit excellent auditory localization capabilities.

In view of the role of acoustical impedance mismatch between water and head, the choice of materials in the design of a dummy head becomes very critical. Surface impedance may not be ignored, thus complicating the design as compared to that for dummy heads in air. If the pinnae are to contribute any directionality to the receiving system, they must be greatly enlarged relative to their counterparts in air. Batteau and Plante (1962) and Batteau (1963) have had reasonable success with underwater localization using an enlarged pinna. Furthermore, it would be beneficial to enlarge the head, both to increase interpinna spacing and to increase the obstacle effect of the head at moderate frequencies. A head of this type should also be made of several parts which are acoustically isolated from one another.

The above considerations suggest that it is probably impractical to design an underwater localization system based solely on an enlarged dummy head. An alternative approach worth investigating is to design an electronic system which would measure and then augment differences in interaural time, phase, and intensity. For example, the intensity difference between receivers of a two-channel system could be monitored, and this information used to control a feedback network to two amplifiers having independent gain controls. Likewise, present technology should allow implementation of an adaptive delay line to augment arrival time differences between the ears.

UNAIDED HUMAN ECHOLOCATION

It has been known for many years that blind humans often possess the ability to detect and avoid obstacles without actually contacting them. The nature of this obstacle sense, which has been misnamed "facial vision" in much of the literature, was not known, however, until very recently. Subjects described the perception as being similar to a veil or curtains near the face (Kohler, 1966; Ammons, et al., 1953). Investigations reported in three papers by researchers at Cornell University finally showed conclusively that audition was both a necessary and sufficient condition for the perception of obstacles (Supa, et al., 1944; Worchel, et al., 1947; Cotzin, et al., 1950). Furthermore, none of the other possible cues including eardrum pressure, temperature changes, or various tactile sensations were found to be necessary or sufficient to elicit the perception.

Subsequent investigators have sought to quantify this obstacle sense in terms of what can be discriminated, within what ranges is the perception operable, and what types of auditory signals are best suited to the perception. It was found that the perception was neither limited to the blind nor to laboratory environments (Kohler, 1964; Ammons, et al., 1953). Sighted subjects who were blindfolded performed as well as blind subjects after considerable practice. Additionally, learning was found to be sudden and insightful, implying that subjects needed merely to recognize the existence of a previously unused perception (Ammons, et al., 1953). It was demonstrated that blind and blindfolded subjects performed detection and discrimination tasks with the same degree of accuracy, whether in the laboratory or in a real-world, outdoor environment (Ammons, et al., 1953).

Various studies have sought to determine what types of signals are optimal for obstacle perception (Cotzin, 1942; Cotzin, et al., 1950; Kohler, 1964; Rice, 1966A, 1966B). While traveling, blind subjects use various types of self-generated stimuli, including clicks, hisses, and the sound of footsteps to elicit the echo perception. Additionally, obstacles can be detected passively through the localization of echoes resulting from background noise (Kohler, 1964; Rice, 1966A). Self-generated signals, however, were found to yield better performance (Kohler, 1964). Rice (1966B) measured performance on various detection and discrimination tasks, allowing subjects to generate whatever signal they wished. He found that subjects were equally divided in their choice of signals, with half using clicks and half using hisses. There were no reliable performance differences between groups using the different signals, and most subjects showed no change in performance when asked to use the nonpreferred sound. It appears to make no difference whether or not the transmitted signal overlaps the echo (Rice, 1966B).

Broadband signals, whether pulsed or continuous, are better suited to echolocation than are narrowband or tonal signals (Griffin, 1958; Basset and Eastmond, 1964; Rice, 1966B). Large time-bandwidth products provide more signal energy, thus making the echoes more detectable (Green, 1960). In two studies reported by Cotzin (1942; Cotzin, et al., 1950), subjects detected obstacles very accurately using thermal noise but were unable to perceive the obstacles using tones with frequencies less than 8 kHz. Cotzin reported that perception was quite good using a 10-kHz pure tone, but as Griffin (1958) suggests, the performance

improvement may have resulted from distortion of the signal since 10 kHz approached the upper frequency limit of Cotzin's electronic equipment. Basset and Eastmond (1964) also report unreliable echo perceptions using tonal stimuli, due to the excitation of standing waves in the test room.

The basis of the obstacle perception seems to be associated with a rise in perceived pitch as obstacles are approached (Cotzin, 1942; Basset and Eastmond, 1964; Wilson, 1966). Loudness changes were found not to be sufficient for obstacle detection (Cotzin, 1942), although they may be valuable for making size discriminations based on target strength (Rice, and Feinstein, 1965). The perceived rise in signal pitch as obstacles are approached may be related to the phenomenon of time-separation pitch (Basset and Eastmond, 1964; Small, et al., 1963; Yost and Hill, 1978). When two broadband stimuli are highly correlated, and one is delayed relative to the other, a pitch is perceived whose frequency is equal to the reciprocal of the time delay.

Numerous investigators have sought to determine what types of detections and/or discriminations can be made via echolocation. While large individual differences exist among subjects' ability to use the obstacle sense, it has been found that the performance of even the best subjects is far inferior to that achievable by some animals, or by the use of auditory sensory aids employing ultrasonic frequencies and directional beam patterns. The following is a summary of detections and discriminations made by the best subjects using self-generated signals.

1. Size and distance. Subjects can detect large objects at distances exceeding five meters (Griffin, 1958). The sizes of just-detectable objects are highly correlated with distance (Rice, Feinstein and Schusterman, 1965; Rice, 1966B; Rice, 1967). At close ranges, disks with diameters as small as 27 mm have been detected (Rice, 1966B). The solid angle which an object must subtend in order to be just detectable was found to be 4.6 degrees and was relatively independent of distance (Rice, Feinstein and Schusterman, 1965). Subjects have been able to discriminate between objects of different sizes having area ratios as small as 1.07/1, with differences in intensity serving as the primary discrimination cue (Rice and Feinstein, 1965).

2. Depth perception. Kellogg (1962) reports that his best subject could accurately discriminate movement of 4.3 inches of a one-foot disk located two feet in front of him.

3. Shape discriminations. Rice (1966B) demonstrated that with practice, most of his subjects could accurately identify squares, circles, and triangles: all objects having the same area. He also found that squares and circles were more detectable than a rectangle having a 16/1 edge ratio. The detectability of the rectangle did not change as a function of whether it was oriented horizontally or vertically. The difficulty in detecting the rectangle was shown to result from a loss of echo intensity in the expected direction.

4. Texture and material composition. Kellogg (1962) showed that subjects could discriminate accurately between objects of the same size made of metal, wood, denim cloth, and velvet. Subjects reported that the various objects simply sounded different. Rice (1966B)

suggests that these discriminations may have been based on differences in target strength. Subject performance was at change level when attempting to discriminate between painted and unpainted wood, or between metal and glass (Kellogg, 1962).

While the types of echo perception discussed in this section are extremely valuable to blind travelers, by no means can they provide a complete spatial representation of the environment. Four major factors limit the usefulness of the obstacle sense.

1. People are limited in the types of signal which they can produce. As will be discussed in the next section, certain advantages can be gained with continuous-transmission FM signals and broadband pulsed signals.

2. The long wavelengths associated with the range of human hearing prevent the return of a sharp sound image, i.e., fine features of objects cannot be discriminated.

3. People cannot transmit a directional beam pattern such that only a small angular region would be ensonified.

4. Because of the large impedance mismatch between air and most surfaces of interest, only initial reflections from the front of objects are returned; that is, internal object structure cannot generally be discriminated in air.

The design of an active sonar system allows a choice of signals and transmitted beam patterns, as well as allowing the use of ultrasonic frequencies, so that the fine features of a target would be large compared to a wavelength. Additionally, many of the disadvantages of underwater hearing become advantages in the design of active underwater sonar systems. That is, the acoustic impedance of water more closely matches that of many solids, so that object echoes can contain information about internal structure. These topics are discussed in the next section on active sonar design.

ACTIVE SONAR SYSTEMS

Since the Second World War, a large number of sonar sensory aids have been developed to enhance blind mobility, e.g., (Witcher and Washington, 1954; Twersky, 1948; Beurle, 1951). Most of these aids have been designed solely for detection of nearby obstacles. That is, they produce an audible signal when an obstacle is near, but they provide no information about the nature of the obstacle (Russell, 1966). A single exception is a series of sensory aids developed by Kay (1962, 1966, 1979), which allow binaural localization of echoes, estimation of distance, and certain types of object discriminations (Kay, 1973).

All of the sonar aids which provide reliable information use directional beam patterns, and broadband, ultrasonic signals which are either heterodyned or digitally stretched into the audible frequency range. The signals used have either been broadband pulses (clicks) or continuous transmission FM (CTFM) signals.

In addition to in-air sonars, considerable work has been done to investigate the sonar capabilities of marine mammals and humans using dolphin-like signals (Au and Hammer, 1978A, 1978B); Nachtigall, et al., 1978; Fish, et al., 1976). Much of the information from these investigations can be applied to the design of underwater sonars for divers. Because the acoustic impedance of water closely matches that of many solids, discriminations of material composition and internal object structure, which are impossible in air, become quite easy using underwater sonars. The advantages of various types of signals and beam patterns, as well as the types of aural discriminations which are possible using high resolution sonars in air and water will be discussed in the following paragraphs.

A vast amount of literature has appeared on the subject of optimum signal design for active sonars. Researchers have sought to determine whether pulsed or continuous waveforms are optimal, what the effect is of varying the pulse shape or sweep rate, and what types of signals are most resistent to various types of interference. The obvious result of these investigations is that the choice of signals depends on the application: whether detection or discrimination, absolute range or range resolution, or doppler information. Different signals are optimum for returning information about detection, discrimination, absolute range, etc.

For any given criterion and time interval, it is generally true that CTFM signals yield a higher probability of detection than do pulsed signals (Kay, 1960). Pulsed signals, on the other hand, yield better range resolution, i.e., the number of objects which can be discriminated in a given range, or the number of details about an object which can be discriminated (Kay, 1960). CTFM signals are probably superior for determining the absolute range to a target and the rate of target motion.

If swept FM signals are used, target detection and range information can be gained by a simple multiplication of the transmitted and received signals to produce a difference frequency (Kay, 1979). The portion of the sweep cycle at which the signal is received is a function of the sweep rate and the two-way travel time of the signal, i.e., the target range. Thus,

if the target is a stationary point reflector, the output of a system which multiplies the transmitted and received signals will be a tone whose frequency is proportional to the target distance. The fact that the system output is tonal causes it to sound very different from background noise, thus resulting in easier initial detections for CTFM sonars as compared to pulsed sonars (Kay, 1960). The bandwidth and sweep rate of the transmitted signal can be adjusted so that frequencies associated with different ranges can be resolved. A very slow sweep rate would not allow fine distance discriminations at close range, whereas a very rapid sweep rate would not allow long-range discriminations. In the design of a CTMF system, it would be beneficial to include a range selector to vary the sweep rate.

Kay (1979) has designed systems with auditory displays which are operable over different ranges, depending on the needs of the user. These systems have been designed so that the received frequency decreases with decreasing distance to the target. The opposite approach, associating high frequencies with close ranges, caused the signals to become nearly inaudible at the point of closest approach to an obstacle.

The output of Kay's CTFM sonar is a pure tone only if the target is stationary and contains no features which are large compared to a wavelength. If the target is in motion the system output is a time-varying tonal complex, and if the target has features of shape or texture which are large compared to a wavelength a complex tonal structure is heard (Riley, 1966; Kay, 1979). Although the frequency resolution of the auditory system required to discriminate between stationary targets is quite poor, it has been demonstrated that if targets are textured or in motion, discrimination is vastly improved (Do and Kay, 1976-77; Kay and Do, 1976-77). The received complex stimuli, which are associated with various classes of objects, can be remembered and in many cases can be generalized to include new objects of a class.

Another beneficial aspect of the Kay sonar aid is binaural presentation of spatial information, allowing simultaneous discrimination of multiple targets (Kay, 1979). With a narrow beam pattern, the environment can be scanned to selectively ensonify various targets or to determine target dimensions (Riley, 1966). With a broad beam pattern, multiple target information can be extracted from the complex tonal display, and directionality can often be interpreted via intensity differences in the two channels. Although directional information has been coded into binaural intensity differences, such coding is range-dependent (Kay, 1979). Thus, new localization cues must be learned when using these systems.

If the sonar has a narrow beam pattern, fine discriminations can be made by scanning, but only radial motion can be perceived. With a wide beam pattern, object motion can easily be perceived, but azimuth resolution is very poor. Multiple targets will always be present in the field of view, whereas a narrow beam sonar requires scanning to determine an object's position. It would certainly be desirable to design a system which allows selection of either a narrow or broad beam pattern. A large portion of the environment could be viewed with the wide beam, and then fine details could be discriminated by scanning with the narrow beam. However, the design of transducer arrays to implement such a system is by no means trivial.

The greatest advantage of the Kay sonar aids over other air sonars is gained in multiple target environments with objects in motion. Binaural presentation of spatial information allows users to perceive motion, and often they can learn to separately localize multiple targets. Because the binaural cues are new, however, subjects require considerable practice before they can accurately translate the lateralized stimuli into three-dimensional spatial perception. Blind and blindfolded subjects have had considerable success at navigating obstacle courses, discriminating walls from fences, and identifying various objects in the environment such as cars and parking meters (Riley, 1966; Kay, 1973; Kay, 1979). Although most objects produce unique and discriminable echoes, the identification of most objects requires context cues. For example, a parking meter would probably not be identified as such in an environment where parking meters are not generally found.

The range resolution capabilities of broadband, ultrasonic, pulse mode sonars would probably be quite useful for object identifications in air. However, the use of broadband pulses as sonar signals has never been tried in air. The following discussion therefore relates the use of pulsed signals for echolocation by dolphins and humans under water. It is difficult to generalize these results to air environments, where only front surface reflections would be returned. However, many bats using pulsed signals have displayed nearly optimal performance on complex echo discrimination tasks.

Dolphins, using very short broadband clicks, have demonstrated the ability to discriminate among targets of various shapes, sizes, and material compositions, as well as various aspects of internal target structure. The following is a brief summary of some of the discriminations which have been accomplished.

1. Size. Dolphins have discriminated between solid steel spheres at close range with 100% correct responses when the spheres had diameters of 5.40 and 6.35 cm (Norris, et al., 1966). Performance dropped to 77% correct when the diameters were 5.7 and 6.35 cm. Differences in echo intensity are probably the most salient discrimination cues. Performance was near 100% correct when discriminating between hollow aluminum cylinders having diameters of 7.6 and 6.35 cm (Au and Hammer, 1978A).

2. Shape. Dolphins have successfully discriminated between cylinders and cubes, independent of target aspect, except for cases in which the flat top of the cylinder was facing the animal (Nachtigall, et al., 1978). These discriminations are based on angular variations in target strength, as well as perception of multiple echoes from surfaces meeting at an edge (Fish, et al., 1976; Nachtigall, et al., 1978).

3. Material composition. Discrimination with 80% correct responses or higher has been demonstrated between dimensionally identical cylinders in the following cases: aluminum vs. rock, aluminum vs. steel, and aluminum vs. bronze (Au and Hammer, 1978A). On a discrimination task involving aluminum and glass cylinders, performance varied from 80% correct to chance as target size was increased.

4. Internal object structure. Discrimination between hollow and solid aluminum cylinders has been shown to be quite easy, with performance near 100% correct. Additonally, dolphins have discriminated between aluminum cylinders having differences in wall thickness of 1.6 mm (Au and Hammer, 1978A). Smaller differences in wall thickness could probably be discriminated, but difference thresholds were not measured in the study cited.

Many attempts have been made to understand the auditory cues which dolphins may use to make echo discriminations. The time series associated with the echo from a target generally involves an initial high-amplitude peak associated with the front surface reflection. A series of secondary reflections follows with decreasing amplitudes. In the case of cylinders, these reflections result from various transverse, circumferential, and square acoustic paths through the material (Shirley and Diercks, 1970). Subsequent reflections along a given path will be periodic with successively decreasing amplitudes. When targets are of very different sizes or materials with large differences in acoustic properties, discriminations can probably be made based on the time series alone. However, when targets are of similar size and composition, the time waveforms do not allow unambiguous discriminations (Au and Hammer, 1978B). Likewise, the power spectrum generally does not supply sufficient information to make the complex discriminations which have been demonstrated. Au and Hammer (1978B) have found a high degree of correspondence between the animals' discrimination performance and a scheme which processes the echoes through a filter whose transfer function is the complex conjugate of the transmitted signal. That is, the matched filter responses for targets which were easily discriminable could be discriminated visually with little problem. However, for targets which were difficult to discriminate the matched filter responses were very similar.

Two major problems with the assumption that matched filters are actually used arise because the transmitted signals for a given animal differ considerably from click to click. The filter would have to be adaptive since no "optimum" signal seems to be used. Secondly, the hypothesis requires that the animal devote a great deal of memory to the storage of exact waveforms (Johnson and Titlebaum, 1976). However, an analysis very similar to matched filters has been invoked to explain the phenomenon of time-separation pitch (Johnson and Titlebaum, 1976). It seems likely that this mechanism of pitch perception associated with the reciprocal of the time interval between correlated reflections might help to explain the mechanisms of echolocation.

Most of the discriminations discussed above would not be possible using CTFM signals unless a bandwidth several times that of the pulsed signals was used. The echo information required for discrimination is separated in time by only a few microseconds (Au and Hammer, 1978B), and the frequency separation necessary to provide this degree of range resolution with CTFM signals would not be practically achievable. Additionally, if an extremely rapid sweep rate were used, so that closely-spaced echoes were resolvable as separate frequencies, the sonar would be of little use for ranges greater than the diameter of the target.

Although not much information is available concerning human listeners using underwater pulsed sonars, several studies have shown that human performance is often as good as

and in some cases better than that of dolphins. Fish, et al. (1976) trained divers to discriminate between various plates one meter in front of them, using a head-coupled sonar and digitally stretched ultrasonic pulses which were produced on the surface. Subjects discriminated between plates which varied in shape (squares, circles, and triangles), material composition (copper, brass, or aluminum) and thickness. The performance of the divers was between 80 and 100% correct, and was in some instances approximately 10% better than that of dolphins on the same task. A subject outside the diving tank who monitored the sonar signals through headphones performed very poorly on all discrimination tasks because he could not coordinate the stimuli with the diver's scanning behavior (Fish, et al., 1976).

Studies presently underway at the Naval Ocean Systems Center, Hawaii Laboratory, have investigated the skill with which humans can discriminate between various types of cylinders differing in composition, size, and wall thickness. Subjects wearing headphones in a sound booth have been asked to discriminate between prerecorded echoes from the various cylinders. The echoes have been digitally stretched to have center frequencies of approximately 2.2 kHz. Under these favorable listening conditions, subjects have been able to make the following discriminations with nearly 100% correct responses.

1. Solid rock vs. hollow aluminum,
2. Solid vs. hollow aluminum,
3. Hollow aluminum – 7.62 vs. 3.18 cm diameter,
4. Hollow aluminum vs. steel,
5. Hollow aluminum vs. bronze.

Subjects have also demonstrated the ability to discriminate between echoes from cylinders which differ only in wall thickness when the difference in wall thicknesses was 1.6 mm. Finally, human subjects have performed at nearly 85% correct when discriminating between hollow aluminum and glass cylinder echoes. Dolphins performed near chance level on a similar task.

The most salient cue in the aluminum-glass discrimination task seems to be a duration difference between echoes. Reflections from the glass cylinders tend to damp out more quickly than those from the aluminum. For cylinders having diameters of 7.6 cm, this duration difference was on the order of 150 microseconds and was apparently not perceptible to the dolphin. However, when the signals are digitally stretched the duration difference is on the order of 7.5 milliseconds. This is readily perceptible to the human subjects as an additional hiss associated with the aluminum targets.

It is probable that differences in time-separation pitch between periodic and highly correlated reflections from the targets provide humans with another salient discrimination cue. The perception of time-separation pitch, in conjunction with duration cues, seem to be the bases for the human discrimination performance in the above studies. In addition to more favorable listening conditions, and the ability to use cues associated with stretching of the signals, human subjects have one other obvious advantage over dolphins on the discrimination

tasks discussed: Training is easier and more precise since humans can understand verbal instructions. Through instructions, they can readily learn to categorize a large number of signals into appropriate classes. A simple explanation is often sufficient to teach subjects to ignore obvious but irrelevant cues.

It seems clear from data cited in this and the previous section that a great deal of information could be gained by equipping a remote sensing system with active and passive echolocation capabilities. While considerable flexibility is available in the design of an air or water sonar, the following general guidelines will aid the resolution and overall utility of the system.

Any high resolution sonar must utilize broadband, ultrasonic signals. Sonars employing pure tones are only capable of returning detection and range information. The use of ultrasound permits the return of a sharp object image, i.e., only object features which are large compared to a wavelength can be discriminated. In addition, high frequency signals can generally be transmitted with smaller and more directional transducers than can low frequency signals.

The use of a narrow beam pattern allows fine discrimination via scanning, whereas a wide beam pattern will ensonify a large area and consequently enhance motion perception. It would probably be desirable to design a system which could employ either of two beamwidths. The wide beam could be used initially to determine if any relevant information will be returned from a given sector, and the narrow beam then could be used to scan for details if objects of interest are detected. Furthermore, the system should allow the operator to select the maximum range of operation. A system which is designed for long-range detection will give very poor depth perception for nearby objects.

Finally, a system utilizing an auditory display should be binaural, and should be coupled to the head rather than hand-held. When scanning with a head-mounted system, the operator will be able to coordinate accurately the direction of the transmitted beam with other auditory and visual sensory information. If the system is not head-mounted, it is difficult to correlate scanning behavior with other localization cues.

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